Title: *Multi-Functional Composite Fatigue* for Proceedings of the **American Society for Composites Twenty-third Technical Conference**

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ABSTRACT

Damage and fracture of composites subjected to monotonically increasing static, tension-tension cyclic, pressurization, and flexural cyclic loading are evaluated via a recently developed composite mechanics code that allows the user to focus on composite response at infinitely small scales. Constituent material properties, stress and strain limits are scaled up to the laminate level to evaluate the overall damage and durability. Results show the number of cycles to failure at different temperatures. A procedure is outlined for use of computational simulation data in the assessment of damage tolerance, determination of sensitive parameters affecting fracture, and interpretation of results with insight for design decisions.

INTRODUCTION

Aerospace propulsion systems are a complex assemblage of structural components that are subjected to a variety of thermal and mechanical loading conditions. Composites are finding increased applications as engine components due to their light weight, relative low cost, and the evolution of automated fabrication processes. Computational simulation methods are becoming increasingly necessary for the design evaluation of composite structures. With the development of new constituent materials and fiber reinforcement configurations, graphite/epoxy composites are becoming more economical for engine fan blade, airbreathing components, first stage compressor, and blade containment structures. Applications of graphite/epoxy fiber composites to engine structures require reliable performance under fatigue loading caused by pressurization cycles, structural vibrations, and fluctuating surface pressures that develop due to the load environment. The relationship between damage evolution characteristics and remaining reliable life need be established for the in-service structural health monitoring of aircraft and engine structures.

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A new laminate analysis and synthesis code developed at NASA Glenn Research Center is called ICAN/JAVA as it is written in Java to allow its usage across the internet. The laminate configuration is not restricted to only plies but can be sliced and subsliced for a closer look at what goes on in the ply sublayers and subregions. The code can be used to model individual fiber-matrix interaction zones and monitor changes at subconstituent levels by subzoning of each subslice.

Several modules have been added to perform durability/fatigue type analyses for thermal as well as mechanical cyclic loads. The code can currently assess degradation due to mechanical and thermal cyclic loads with or without a defect. Thermal loads, hygral loads and electrical loads can now be input as constant, linear, parabolic, hyperbolic or user defined across the ply-lay-up. A damping analysis under dynamic cycling has been incorporated. Details regarding chemical reactions of fiber and matrix constituents can also be input in the new version. Damage tracking due to impact of a hard spherical projectile crashing into the composite can also be considered in this version. The method is able to simulate damage initiation, damage growth, and fracture in fiber composites under various loading, considering also the effects of residual stresses and environmental conditions. The objective of the current paper is to demonstrate the new spatially consistent simulation capability that evaluates progressive damage and fracture of composite structures subjected to cyclic fatigue at the progressively zoomed subslice and subregion levels, including the effects of temperature. Constituent material properties, stress and strain limits are scaled up to the laminate level to evaluate the overall damage and fracture propagation for composites. Damage initiation, growth, accumulation, and propagation to fracture due to cyclic loads are included in the simulations. Results show the number of cycles to failure at different temperatures and the damage progression sequence during different degradation stages. A procedure is outlined for use of computational simulation data in the assessment of damage tolerance, determination of sensitive parameters affecting fracture, and interpretation of results with insight for design decisions. The fundamental premise of computational simulation is that the complete evaluation of laminated composite fracture requires an assessment of ply and subply constituent material level damage/fracture processes.

METHODOLOGY

Computational simulation assumes that the complete evaluation of laminated composite fracture requires an assessment of ply and constituent material level damage/fracture processes. Computational simulation by-passes traditional fracture mechanics to provide an alternative evaluation method, conveying to the design engineer a detailed description of damage initiation, growth, accumulation, and propagation that would take place in the process of ultimate fracture of a composite structure. Results show in detail the damage progression sequence and fatigue damage characteristics during different degradation stages.

The evaluation of local damage due to cyclic loading is based on simplified mathematical models embedded in the composite mechanics code. The fundamental assumptions in the development of these models are the following: (1) Fatigue degrades all ply strengths at approximately the same rate [1]. (2) Fatigue degradation may be due to: (a) mechanical (tension, compression, shear, and bending); (b) thermal (elevated to cryogenic temperature); hygral (moisture); and combinations (mechanical, thermal, hygral, and reverse-tension compression). (3) Laminated composites generally exhibit linear behavior to initial damage under uniaxial and combined loading. (4) All ply stresses (mechanical, thermal, and hygral) are predictable by using linear laminate theory.

Under fatigue loading ply, sublayer, and subregion failure modes are assessed by using margins of safety computed by the composite mechanics module via superposition of the six cyclic load ratios. The cyclic loads that are considered are the N_x, N_y, N_{xy} in-plane loads and M_x, M_y, M_{xy} bending moments per unit width of laminate. The lower and upper limits of the cyclic loads, the number of cycles, and the cyclic degradation parameters are supplied to the composite mechanics code for the computation of a complete failure analysis based on the maximum stress criteria and Miner's rule. The composite mechanics module with cyclic load analysis capability evaluates the local composite response subjected to fluctuating stress resultants. The number of cycles required to induce local structural damage are evaluated. After damage initiation, composite properties are reevaluated based on degraded ply properties and the overall structural response parameters are recomputed. Iterative application of this computational procedure results in the tracking of progressive damage in the composite structure subjected to cyclic load increments. The number of cycles for damage initiation and the number of cycles for structural fracture are identified in each simulation. Within each ply the fiber and/or matrix properties are degraded as appropriate according to the dominant failure mode. The type of damage growth and the sequence of damage progression depend on the composite structure, loading, material properties, and hygrothermal conditions [2]. No assumptions are made regarding the damage mode controlling progressive fracture. All damage processes are quantified according to the constituent material properties.

FATIGUE DEGRADATION MODELS

The simplest degradation model is based on the assumption that all material properties may be assumed to diminish linearly on a logarithmic scale based on the number of cycles endured [3].

$$\frac{P}{Po} = 1 - \beta \log N \tag{1}$$

Where P is the current value of a property, Po is the original value of the same property, β is the logarithmic degradation coefficient, and N is the number of load cycles. The log-linear degradation model is fairly effective in describing the cyclic fatigue response of a composite or metallic material that is loaded under a constant type of loading and uniform hygrothermal environment. A more general degradation model can be constructed to take into account temperature, state of stress, and other environmental effects. Influences of different effects on fatigue life can be represented by a Multi-Factor Interaction Model (MFIM) [4]. The fundamental premise of MFIM is that material behavior constitutes an n-dimensional space that is called Material Behavior Space (MBS) where each point represents a specific aspect of material behavior. It is further reasonable to assume that MBS can be described by an assumed interpolation function. One convenient interpolation function is a polynomial of product form because mutual interactions among different factors can be represented by the overall product, and includes those cross products in common algebraic polynomials. In this investigation, MBS is assumed to be described by the following multifactor interaction equation (MFIM):

$$\frac{M_P}{M_{Po}} = \prod_{i=1}^{N} A_i^{mi} \tag{2}$$

Where M_P is the property affected to be evaluated. M_{Po} corresponds to the initial (reference) material state or condition. A_i represents the ith factor that influences material behavior, and m_i is an exponent. A_i is further defined by:

$$A_i = \left(1 - \frac{B}{B_o}\right)_i \tag{3}$$

Here B represents a specific cause factor for behavior (for example, temperature), and B_o is the corresponding final value. Values for B_o and m_i for specific behavior are selected either from known behavior or more likely from a best judgment in conjunction with consultations with seasoned professionals for that behavior.

By representing the MBS with the MFIM of product form (eq. (2)), we gain another distinct advantage. The behavior factors, B, can also be represented by another level of MFIM or progressive substructuring of equation (2). The progressive substructuring leads to a multi-tier representation of the MBS that permits intrinsic lower tier behaviors to influence more than one factor at the next higher tier. In other words, the observed specific behavior B_i may depend on another set of lower tier elemental behaviors. Further, the behavior factors in this lower set of specific behaviors may depend on yet another next lower tier of elemental behaviors. That is, there are usually sets and subsets of specific behaviors that hierarchically influence the higher level behaviors. This representation is natural for multiparallel processing computers where the tiers are programmed with different granularities. Obviously, then, the motivation for selecting such a form is for computational and programming effectiveness. Another reason for selecting an MFIM of product form is that the effect of each factor can be evaluated separately. The interpretation of B_o is that it represents a scale, whereas m_i represents a shape or path. For example, $(1 - B/B_o)^{m_i}$ where $1 > B/B_o$. and $+ 8 < m_i < - 8$, covers the whole MBS space. The inclusiveness of this particular form, combined with its simplicity, makes it very attractive for computational simulation.

GRAPHITE/EPOXY COMPOSITE STRUCTURES

We consider a quasi-isotropic graphite/epoxy $[0/\pm45/90/0/\pm45/90]_s$ laminate that was flexural fatigue tested at a temperature of 160 °F. Fatigue life details are listed as follows. Analyses with and without subslicing are included. Table I indicates that the ICAN/JAVA code with subslicing detects local stress concentrations within plies and therefore is more conservative for design simulations under thermal fatigue.

Composite Coupon Under Tension-Tension Fatigue

We consider a quasi-isotropic graphite/epoxy $[45/90/–45/0]_s$ 1.0- by 6.0-in. coupon that was tension-tension fatigue tested at temperatures of t = –195, +22, and +121 °C by Uleck et al [5]. Figure 1 compares the log-linear degradation described by the logarithmic decrement model for the quasi-isotropic graphite/epoxy composite subjected to 22 °C room temperature cyclic loading at different load amplitudes with corresponding test data. The logarithmic degradation coefficient β is 0.06 in Figure 1. The model is a good log-linear fit to the test data. However, the logarithmic decrement model is not able to distinguish between the different temperatures.

TABLE I. EFFECT OF SUBSLICING ON THERMAL FATIGUE

ICAN/JAVA (without subslicing)	
Most likely ply to fail first due to thermal fatigue	15
Ply Orientation	45
Ply Material	T300/IMHS
Allowable Transverse Strength “SL22T”	12844.277
Residual Stress due to Curing “SIG22”	20475.199
DELTA T	160.000
Ratio “SIG22/SL22T”	1.594
ICAN/JAVA (with subslicing = 9)	
Most likely ply to fail first due to thermal fatigue	15:125
Ply Orientation	45
Ply Material	T300/IMHS
Allowable Transverse Strength “SL22T”	12844.277
Residual Stress due to Curing “SIG22”	21829.020
DELTA T	160.000
Ratio “SIG22/SL22T”	1.700

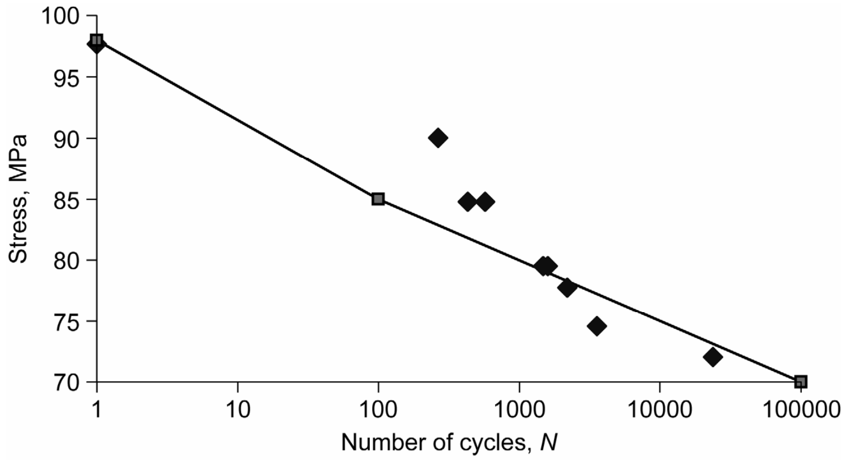

Figure 1. Logarithmic decrement model for cyclic fatigue (β=0.06).

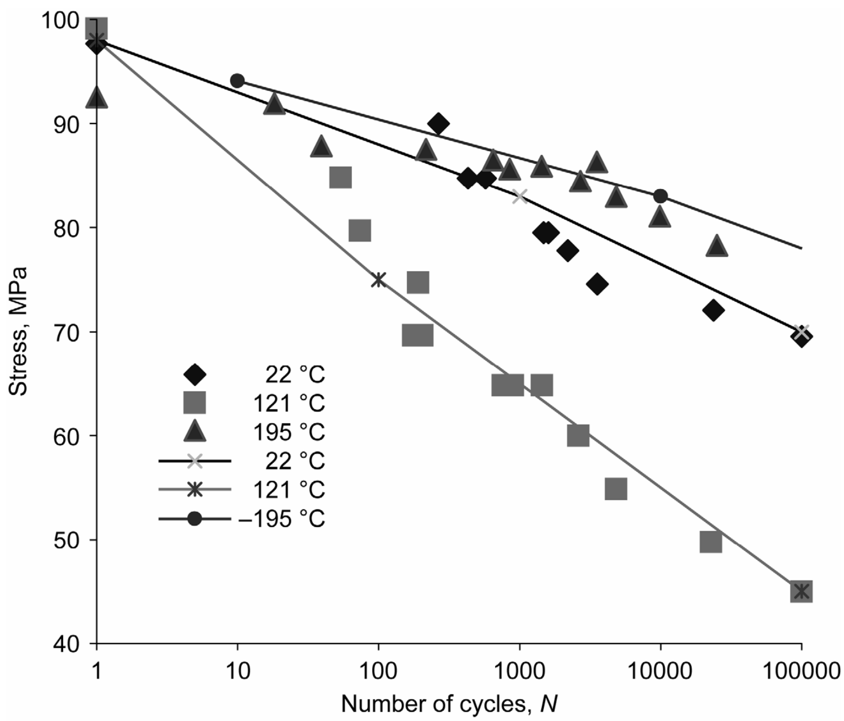

Figure 2. MFIM for cyclic fatigue at different temperatures.

To take the temperature effects into account, the Multi-Factor Interaction Model is set up in the form of:

$$\frac{P}{Po} = \left(\frac{tgw - t}{tgw - to}\right)^{mt} \left(1 - \frac{\sigma}{S}\right)^{ms} \left(1 - \left\{\frac{tgw - t}{tgw - to}\right\}^{mtn} \frac{\sigma_M N_M}{S.N_{Mf}}\right)^{mn} \tag{4}$$

Where t_{gw}=204 °C, t_o=21 °C, S=98 Mpa, N_{Mf}=100000, mt=0.5, ms=0.5, mn=0.75, mtn=0.75 for t>22 °C, mtn=0 for t<22 °C. Figure 2 compares the MFIM simulation results with the test data for all three temperatures. The MFIM based computational simulation was able to include the temperature effects in a single MFIM equation inserted into the composite mechanics durability analysis module. The agreement between computational simulations and test data is reasonable for preliminary design investigations under fatigue loading. The AS-4 graphite fiber properties used in the simulation are given in Table II and the intermediate modulus Epoxy matrix properties are given in Table III.

TABLE II. AS-4 FIBER PROPERTIES

Number of fibers per end	10000
Fiber diameter	0.00762 mm (0.300×10^{-3}in.)
Fiber Density	4.04×10^{-7} Kg/m^3 (0.063 lb/in^3)
Longitudinal normal modulus	227 GPa (32.90×10^6 psi)
Transverse normal modulus	13.7 GPa (1.99×10^6 psi)
Poisson's ratio (ν_{12})	0.20
Poisson's ratio (ν_{23})	0.25
Shear modulus (G_{12})	13.8 GPa (2.00×10^6 psi)
Shear modulus (G_{23})	6.90 GPa (1.00×10^6 psi)
Longitudinal thermal expansion coefficient	-1.0×10^{-6}/°C (-0.55×10^{-6}/°F)
Transverse thermal expansion coefficient	1.0×10^{-5}/°C (0.56×10^{-5}/°F)
Longitudinal heat conductivity	43.4 J-m/hr/m^2/°C (580 Btu-in./hr/in.^{2}/°F)
Transverse heat conductivity	4.34 J-m/hr/m^2/°C (58 Btu-in./hr/in.^{2}/°F)
Heat capacity	0.712 KJ/Kg/°C (0.17 Btu/lb/°F)
Tensile strength	3.723 GPa (540 ksi)
Compressive strength	3.351 GPa (486 ksi)

TABLE III. INTERMEDIATE MODULUS EPOXY MATRIX PROPERTIES

Matrix density	3.27×10^{-7} Kg/m^3 (0.0440 lb/in.^{3})
Normal modulus	3.65 GPa (530 ksi)
Poisson's ratio	0.35
Coefficient of thermal expansion	0.648×10^{-4}/°C (0.360×10^{-4}/°F)
Heat conductivity	0.654×10^{-3} J-m/hr/m^2/°C (0.868×10^{-8} Btu-in./hr/in.^{2}/°F)
Heat capacity	1.047 KJ/Kg/°C (0.25 Btu/lb/°F)
Tensile strength	110.9 MPa (15.5 ksi)
Compressive strength	242 MPa (35.0 ksi)
Shear strength	89.7 MPa (13.0 ksi)
Allowable tensile strain	0.02
Allowable compressive strain	0.05
Allowable shear strain	0.035
Allowable torsional strain	0.035
Void conductivity	16.8 J-m/hr/m^2/°C (0.225 Btu-in./hr/in.^{2}/°F)
Glass transition temperature	216 °C (420 °F)

Composite Shell Under Pressurization Cycles

Another application of the MFIM simulation is the pressurization cycles of a quasi-isotropic $[45/90/{-45}/0]_s$ graphite/epoxy composite cylindrical shell. Pressurization of a cylindrical shell induces a biaxial stress state where the axial stresses are half those of the hoop stresses. Figure 3 shows the MFIM simulations for the three temperatures considered. For all three temperatures the damage progression characteristics may be outlined by the following stages:

1. Damage initiation is by transverse tensile failures in the 0° plies.
2. Damage growth is by longitudinal compressive failures of the 0° plies due to the weakened matrix support.
3. Damage accumulation is by transverse tensile failures of the 90° and ±45° plies.
4. Damage propagation by the longitudinal compressive failure of the 90° plies.
5. Structural fracture occurs by the longitudinal tensile failures of the surface +45° plies.

The reduction of the number of cycles to failure at high temperatures is mainly due to the inability of the material to dissipate the generated hysteretic internal energy and the additional deformability of the material at the higher temperature. At the low temperature of –195 °C, even though the material becomes brittle, its cyclic energy is reduced and the ability to dissipate the energy is improved, thereby extending the fatigue life. The simulation of composite shell pressurization fatigue is conservative due to the beneficial effects of the biaxial tension stress state.

PRACTICAL USES OF COMPUTATIONAL SIMULATION

The ICAN/JAVA computational simulation method with progressive region decomposition is suitable for the design and continued in-service evaluation of composites subjected to cyclic loading. Composite structures with different constituents and ply lay-ups can be evaluated under cyclic loading and pressurization. The cyclic load amplitude and the environmental temperature may be

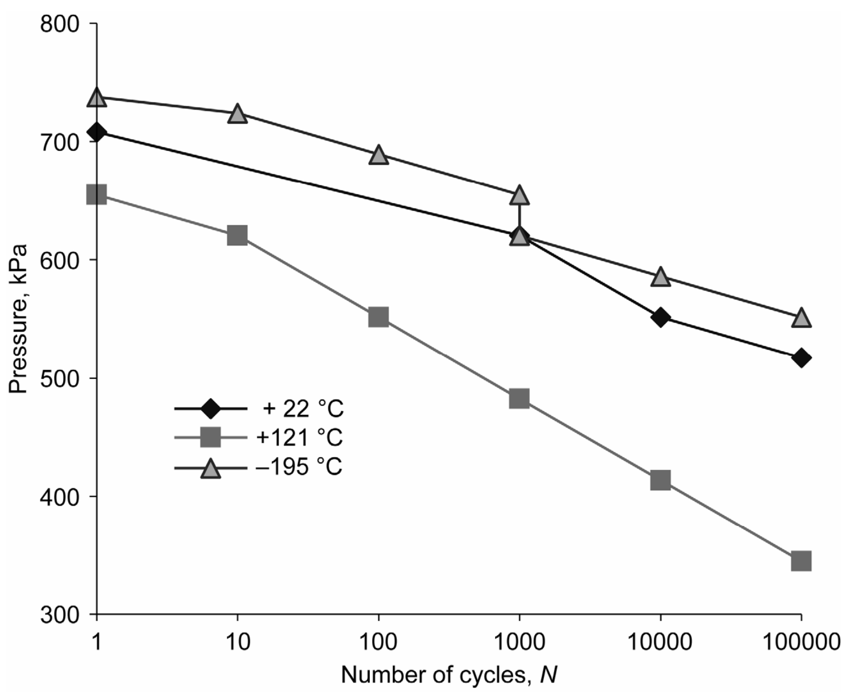

Figure 3. MFIM simulations of composite shell fatigue.

varied during the simulated fatigue life. Static and dynamic load combinations may also be applied in addition to cyclic loading.

Structural health monitoring is based on damage tolerance requirements defined via the computational simulation method. Identification of damage progression mechanisms and the sequence of progressive fracture modes conveys useful information to evaluate structural safety. Computational simulation results can be formulated into health monitoring criteria, increasing the reliability of composite structures. The simulated failure modes and the type of failure provide the necessary quantitative and qualitative information to design an effective health monitoring system. Computed local damage energy release rates are correlated with the magnitudes of acoustic emission signals and other damage monitoring means such as magnetic or piezoelectric stress sensors and strain gages that are an integral part of the monitored composite structure. Fiber optics data networks embedded in the composite structure would transmit the detected local damage information to an expert system that provides feedback and reduces engine power to delay failure.

The basic procedure is to simulate a computational model of the composite structure subjected to the expected loading environments. Various fabrication defects and accidental damage may be represented at the ply and constituent levels, as well as at the laminate level. Computational simulation may be used to address various design and health monitoring questions as follows:

1. Evaluation of damage tolerance: Computational simulation will identify the damage that would be caused due to cyclic fatigue damage or overloading by the type of load the structure is designed to carry. On the other hand, a fabrication defect or accidental damage produced by inadvertent loading that is not an expected service load can be included in the initial computational model. Once the composite damage is defined, damage tolerance can be evaluated by monitoring damage growth and progression from the damaged state to ultimate fracture. Identification of damage initiation/progression mechanisms and the sequence of progressive fracture modes convey serviceable information to help with critical decisions in the structural design and health monitoring process. Determination of design allowables based on damage tolerance requirements is an inherent use of the computational simulation results. Simulation of progressive fracture from defects allows setting of quality acceptance criteria for composite structures as appropriate for each functional requirement. Detailed information on specific damage tolerance characteristics help establish criteria for the retirement of a composite structure from service for due cause.
2. Determination of sensitive parameters affecting structural fracture: Computational simulation indicates the damage initiation, growth, and progression modes in terms of a damage index that is printed out for the degraded plies at each damaged node. In turn, the damage index points out the fundamental physical parameters that characterize the composite degradation. For instance, if the damage index shows ply transverse tensile failure, the fundamental physical parameters are matrix tensile strength, fiber volume ratio, matrix modulus, and fiber transverse modulus, of which the most significant parameter is the matrix tensile strength [3]. In addition

to the significant parameters pointed out by the ply damage index, sensitivity to hygrothermal parameters may be obtained by simulating the composite structure at different temperatures and moisture contents [2]. Similarly, sensitivity to residual stresses may be assessed by simulating the composite structure fabricated at different cure temperatures. Identification of the important parameters that significantly affect structural performance for each design case allows optimization of the composite for best structural performance. Sensitive parameters may be constituent strength, stiffness, laminate configuration, fabrication process, and environmental factors.

3. Interpretation of experimental results for design decisions: Computational simulation allows interactive experimental-numerical assessment of composite structural performance. Simulation can be used prior to testing to identify locations and modes of composite damage that need be monitored by proper instrumentation and inspection of the composite structure. Interpretation of experimental data can be significantly facilitated by detailed information from computational simulation.

An illustration of the procedure just described is the prediction composite strength degradation as a function of cycle numbers using the MFIM with an exponent of 1.5 results in the composite strength degradation shown in Figure 4. By changing the exponent in the MFIM to 0.1, it results in the curves shown in Figure 5. Note that the results in Figures 4 and 5 are for three fatigue simultaneous cycles applied in the *X*-direction $N_{cxx,}$ in the *Y*-direction N_{cyy} and in plane shear N_{cxy}. To the authors' these are the first results for simultaneous fatigue under combined cycles. It is interesting to note that the results plotted in Figures 4 and 5 are of the same magnitude strictly for convenience. Any ratio could easily be applied as well as thermal and moisture conditions simultaneously. The notation in Figures 4 and 5 is as follows: S_d denotes degradation strength; S_o denotes single cycle strength.

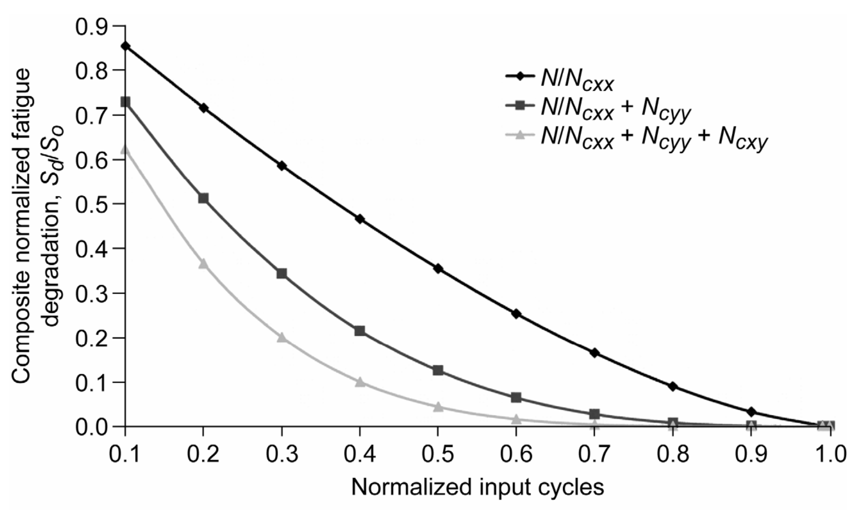

Figure 4. Combined fatigue cycles predicted by the multifactor equation model with exponent = 1.5.

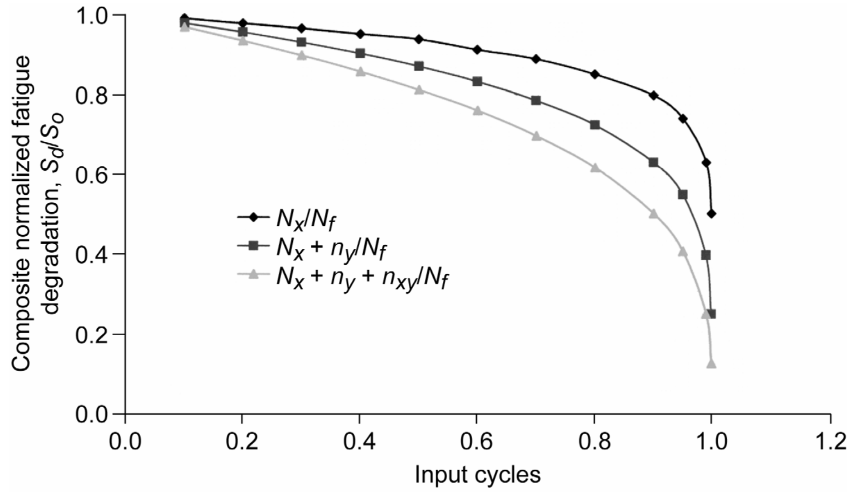

Figure 5. Combined cyclic fatigue with exponent of 0.1 as predicted by the MFIM.

CONCLUSIONS

On the basis of the results obtained from the investigated composites and from the general perspective of the available computational simulation method, the following conclusions are drawn:

1. The number of cycles to structural failure can be evaluated via computational simulation.
2. Effects of different temperatures can be taken into account using a multi-factor interaction model.
3. Computational simulation can be used to track the details of damage initiation, growth, and subsequent fracture of composite structures subjected to cyclic fatigue.
4. For the example composite structures considered, damage evolution characteristics can be identified.
5. Computational simulation, with the use of established composite mechanics and finite element modules, can be used to predict the influence of composite geometry as well as loading and material properties on the durability of composite structures.
6. The demonstrated procedure is flexible and applicable to all types of constituent materials and loading. Hybrid composites and homogeneous materials, as well as laminated, stitched, woven, and braided composites can be simulated.
7. The MFIM model can also be successfully used for evaluating the simultaneously composite degradation strength under multi-axial fatigue cycles.
8. A new general methodology has been demonstrated to investigate damage initiation, growth, and fracture of composite structures due to cyclic loading.

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